Near-Earth Object Surveyor Overview

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Abstract— **The Near-Earth Object (*NEO*) Surveyor is designed to detect, categorize and characterize Near-Earth Objects (NEOs) using infrared imaging. The project was approved to enter the preliminary design phase (Phase B) in FY21 after an extended Concept Development Phase (Phase A). The *NEO Surveyor* project responds to US Public Law 109-155[1], National Research Council's report "Defending Planet Earth: Near-Earth Object Surveys & Hazard Mitigation Strategies (2010)"[2], the U. S. National Near-Earth Object Preparedness Strategy and Action Plan (June 2018)[3], and the objectives of NASA's Planetary Defense Coordination Office (PDCO). The goals of the *NEO Surveyor* project are to: (1) identify impact hazards to the Earth posed by NEOs (defined as asteroids and comets that come within 1.3 AU of the Sun) by performing a comprehensive survey of the NEO population; (2) obtain detailed physical characterization data for individual objects that are likely to pose an impact hazard; (3) characterize the entire population of potentially hazardous NEOs to inform potential mitigation strategies. The mission will make significant progress toward the George E. Brown, Jr. NEO Survey Program objective defined by the U. S. Congress of detecting, tracking, cataloging, and characterizing at least 90% of NEOs equal to or larger than 140 m in diameter. The project is a collaboration between NASA-JPL, the University of Arizona (UA) and industry, with Ball Aerospace notably providing the spacecraft and key instrument elements. This paper will describe the overall *NEO Surveyor* Project objectives, initial spacecraft and instrument design and development plans and mission concept.**

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1. INTRODUCTION

The *Near Earth Object* (*NEO*) *Surveyor* project is a directed mission within the Planetary Defense Coordination Office (PDCO) which is part of the NASA Planetary Science Division within the Science Mission Directorate. Its primary objective is to detect the asteroids and comets that come within 1.3 AU of the Sun, a population of small bodies known as the near-Earth objects (NEOs). The mission was selected to enter into NASA project Phase B in June of 2021 after four years of Phase A development [5]. The project is managed by Jet Propulsion Laboratory (JPL) for NASA as part of the

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Planetary Missions Program Office portfolio. The Survey Director Prof. Amy Mainzer is located at UA and the Science Data System is located at Caltech's Infrared Processing and Analysis Center (IPAC). The major partners for the mission are Ball Aerospace (Ball) which is building the spacecraft, cryogenic instrument components and aperture cover, and Space Dynamics Laboratory (SDL) which is building and integrating portions of the instrument.

The *NEO Surveyor* mission was selected to enter into pre-Phase A as part of the Discovery-14 in 2017 as the Near-Earth Object Camera (NEOCam) project. During extended Phase A from 2017-2021 the project team matured key technologies within the instrument required for the project to successfully enter into Phase B in June of 2021.

The *NEO Surveyor* mission builds on the success of NASA's Wide-field Infrared Survey Explorer (WISE) mission [4], which launched in December, 2009 into low Earth orbit and surveyed the entire sky in four infrared wavelengths during its six-month baseline mission. Following successful completion of its prime mission and a lengthy hibernation, WISE was reactivated in December 2013. The mission was renamed the Near-Earth Object Wide-field Infrared Explorer (NEOWISE)[5], with its objective now to search for and characterize the asteroids and comets that come closest to Earth. The WISE/NEOWISE mission, while not optimized to search for NEOs, has proven to be a useful precursor mission for the *NEO Surveyor*, having detected more than a thousand NEOs [6] and over 100,000 more distant asteroids and comets [7]. NEOWISE is anticipated to re-enter Earth's atmosphere in 2025.

The *NEO Surveyor* mission leverages the experience gained from WISE/NEOWISE and is optimized for the discovery of large numbers of NEOs. This paper provides an overview of the mission goals of the project along with descriptions of the mission design, spacecraft and instrument systems which will provide the data needed to detect these objects. For more mission background information refer to prior *NEO Surveyor* papers in the reference section.

2. Science Requirements

The primary objective of the *NEO Surveyor* mission is to find and catalog the majority of potentially hazardous NEOs greater than 140 m in effective spherical diameter, which are large enough to cause severe regional damage, during the *NEO Surveyor* five-year operational phase. This objective is the primary driver of the mission's design and operations. The observatory will execute an observational cadence optimized for discovering NEOs, which typically have faster apparent on-sky motions than the majority of more distant objects in the main asteroid belt and beyond. The cadence is designed so that objects are detected enough times over a sufficient timespan so that they can be recovered at subsequent apparitions without needing additional ground-based follow up observations.

Other top-level mission objectives include characterizing the numbers, size distribution, and orbital properties of the population of near-Earth asteroids that are between 50-140 m in diameter (i.e. large enough to cause damage to a city) as well as short- and long-period comets. The mission additionally has the capability to interrupt regular survey operations to point at specific targets of interest in the event that objects with unusually high impact probabilities are discovered.

3. Mission Description

The *NEO* Surveyor mission is optimized for the detection, categorization and characterization of NEOs and has no other science objectives. The two wavelengths (4.0-5.2 um and 6-10 um; denoted NEO Surveyor Channel 1 (NC1) and denoted NEO Surveyor Channel 2 (NC2) were chosen to maximize sensitivity to NEOs, which tend to have temperatures close to 250-300K. Since NEOs with the most Earth-like orbits have the potential to make close approaches most often to Earth, *NEO Surveyor* is designed to image near-Sun regions of the sky where the density of such objects is highest. To detect objects with long synodic periods, the mission must last for approximately five years.

To maximize mission lifetime, the *NEO Surveyor* uses long-wavelength HgCdTe detector arrays for both NC1 and NC2 that can be cooled to their operating temperature of 40 K purely passively [8], [9], [10].

To facilitate passive cooling as well as enable a high data rate that stays constant over the course of the mission, *NEO Surveyor* will operate in a halo orbit around the Sun-Earth L1 Lagrange point. This orbit minimizes the IR interference on the detectors from the Earth while allowing for daily high-rate downlinking of the 32 Megapixel full frame images taken every 30 seconds. By downlinking full frame images, asteroids and comets can be extracted from the data using conventional image processing algorithms. Moreover, preserving the full frame images allows them to be searched post facto for additional detections long after the original data processing is complete for so-called "precovery" observations of future discoveries.

4. Mission Design

NEO Surveyor's mission design profile is simple and low-risk with flexible launch date opportunities, low energy insertion with little-to-no ΔV cost, minimal orbit maintenance, and ample propellant margins. *NEO Surveyor* will orbit a large-amplitude halo around the Sun-Earth L1 libration point. The selected L1 orbit provides excellent Potentially Hazardous Asteroid (PHA) viewing geometry, short-range communications using near-Earth bands, and a stable, cold thermal environment that supports passive cooling. This low energy orbit requires no deterministic ΔV and no time-critical operations to attain. The trajectory is easy to maintain with high-accuracy navigation at all times, resulting in low-risk mission operations.

4.1 Launch, Cruise, and Halo Orbit Insertion

The operational trajectory chosen for *NEO Surveyor* has been used successfully on previous missions, including SOHO, Genesis, and ACE [11]. *NEO Surveyor* will be launched from the Eastern Test Range directly to a large-amplitude Sun-Earth L1 halo orbit and is capable of launching on almost any day of the year: 346 out of 365 days are favorable launch days in terms of C3 values and lunar closest approach distance. In 2026, only 19 out of 365 trajectories encounter the Moon at a distance less than 100,000 km (but greater than 50,000 km). Even excluding these 19 days, *NEO Surveyor* is capable of launching 95% of the time. The 21-day launch period starts on March 23, 2026 with 30 second daily launch windows. The launch C3 value during the selected launch period ranges from -0.64 to -0.54 km2/s2. The closest lunar distance during the current launch period is greater than 100,000 km, presenting no additional complexity due to lunar perturbations on the outbound trajectory. For reference, the *NEO Surveyor* baseline trajectory corresponding to the nominal launch date of March 23, 2026 is illustrated in Figure 1. The cruise trajectory is "ballistic" in that the three planned Trajectory Correction Maneuvers (TCMs) are included only to correct launch vehicle insertion errors. The TCMs are not time-critical events, reducing operational complexity and risk.

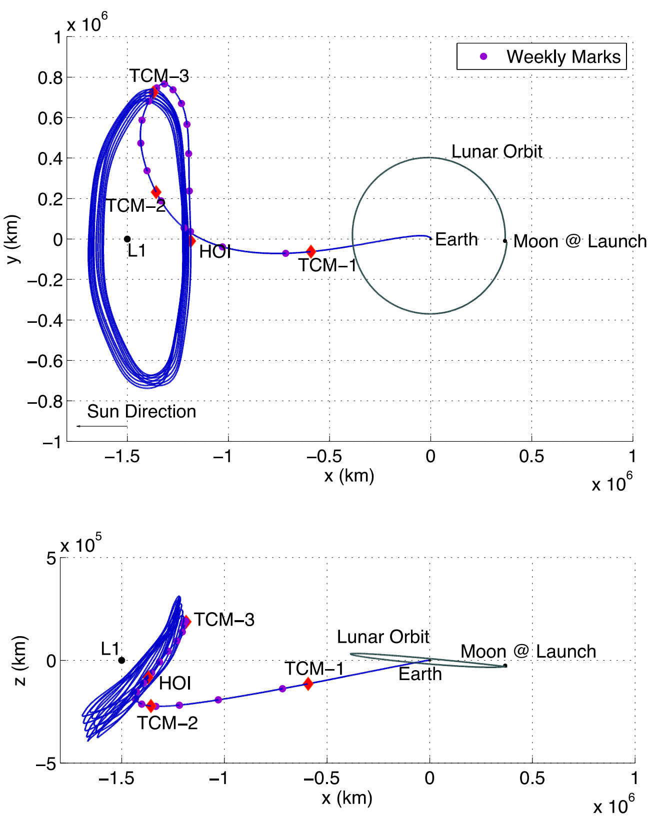

Figure 1: *NEO Surveyor* reference trajectory depicted in Earth-centered, Sun-Earth rotating frame with nominal launch date of 23-Mar-2026. The L1 halo orbit requires only three TCMs to achieve, minimizing operational complexity and cost**.**

Leveraging Sun-Earth multi-body dynamics, the *NEO Surveyor* trajectory is ballistic from launch to the end of mission and is maintained via small, statistical maneuvers that are not time-sensitive. A statistical ΔV of 71.2 m/s is required for the baseline 5-year mission. *NEO Surveyor* design allows for a ΔV of 110 m/s (sufficient for more than 10 years of operation) . The ΔV budget accounts for cruise orbit insertion errors, TCMs, and station-keeping maneuvers.

NEO Surveyor's orbit design also provides flexibility in terms of trajectory correction maneuver execution time. The approximately 114-day transfer leg spans from upper stage separation to arrival in the science orbit and is maintained with three statistical correction maneuvers: TCM-1, scheduled 5 days after launch, is designed to remove any launch injection errors and TCM-2 and TCM-3, at 30 and 60 days after launch respectively, are designed to navigate *NEO Surveyor* to the survey orbit. In contingency situations, these maneuvers can be re-attempted within 20 days and 30 days, respectively, for a ΔV penalty of less than 1 m/s. The L1 Halo Orbit Insertion (HOI) is also a statistical, non-time critical

Table 1 Mission Design Summary and Orbit Parameters

Baseline Launch Date	March 23, 2026
Launch Energy	-0.64 km^2/s^2
Launch Inclination	28.5 ^{degrees}
Orbit Type	Sun-Earth L_1 quasi-halo orbit
Cruise Duration to OI	114 days
In-Orbit Checkout	30 days (during cruise)
Total Mission Duration	63 months
Orbit Parameters	
Orbit Size	744,000km (Y) $\times$ 351,000km (Z)
Orbit Period	~180 days (wrt Sun-Earth L_1)
Sun to L_1 Distance	~148.1 million km
Earth to L_1 Distance	~1.5 million km
Statistical Maneuver Schedule and Budget	
TCM-1	5 days after launch (34.8 m/s)
TCM-2	30 days after launch (3.0 m/s)
TCM-3	60 days after launch (0.5 m/s)
Orbit Insertion Maneuver	114 days after launch (0.5 m/s)
Station-Keeping Maneuvers	Every 90 days (1.0 m/s per year)
Total ΔV for 5-year Baseline Mission	71.2 m/s, 39 kg of propellant

maneuver. HOI can be attempted again within 2 weeks for a ΔV increase of less than 0.1 m/s, if necessary. After a 114-day cruise to the vicinity of L1, insertion into the selected halo orbit requires a small ΔV of approximately 0.5 m/s. Thereafter and given the unstable nature of the selected halo orbit, station-keeping maneuvers are required approximately every 90 days to ensure that the Observatory remains close to its nominal path. A variety of targeting techniques are available to control the path of the spacecraft using minimum propellant [12].

For conservatism, the ΔV budget includes contingency for two possible effects: 16.2 m/s for a 4-day delay of TCM-1, and 11.2 m/s to decompose the TCMs into two maneuvers in order to meet Sun pointing constraints. TCM-1, in particular, may require that the optimal maneuver attitude point the observatory +Z axis toward the Sun, which would illuminate the FPM radiator. To protect the radiator from unnecessary heating, a pointing exclusion zone of 35 degrees is maintained with the aperture cover on. This constraint can be maintained by decomposing a maneuver into two segments. Although not time critical, TCM-1 and the aperture cover release are critical events. The aperture cover ejection occurs 14 days after launch, under real-time control.

4.2 Science Operations

During Science Operations, *NEO Surveyor* performs a repetitive survey pattern, covering the area from 45–120 degrees solar ecliptic longitude (on both sides of the Sun) and ±40 degrees ecliptic latitude. The repetitive survey pattern is shown in Figure 2. Each field on the sky is visited 4 times over ~6 hours to form tracklets and then revisited ~13 days later to enable tracklet linking.

NEO Surveyor's default observation (called a Visit) lasts 180 seconds and is composed of six separate Exposures to avoid saturating on the zodiacal background and to suppress the impacts of cosmic rays. The individual Exposures are dithered in a hexagonal pattern with 10 arcsec steps between dither positions to suppress the impacts of noisy pixels.

To enable tracklet formation, 4 object detections are required over the span of 8±4 hours. The survey accomplishes this by looping around a 16×2 grid of fields, performing a Visit at each field before slewing to the next. Each of these Loops takes a total of ~2 hours, including Visits to 32 fields and the associated slews. Four Loops (defined as a Quad) take ~8 hours and result in 4 Visits to each field spanning ~6 hrs. Source detections from the 4 Visits are assembled into tracklets and reported to the Minor Planet Center.

Each Quad covers >13 degrees in ecliptic latitude and ~25 degrees in longitude, with fields oriented such that the sunshade is aligned toward the Sun, and overlapping by >0.1 degrees. A set of six Quads, arranged in latitude, are obtained to form a Stack. *NEO Surveyor* then slews in longitude and repeats this pattern. Over ~6.6 days, three adjacent Stacks (a Side) cover an entire side of the sky from ±40 degrees latitude and 45–120 degrees solar elongation. After slewing across

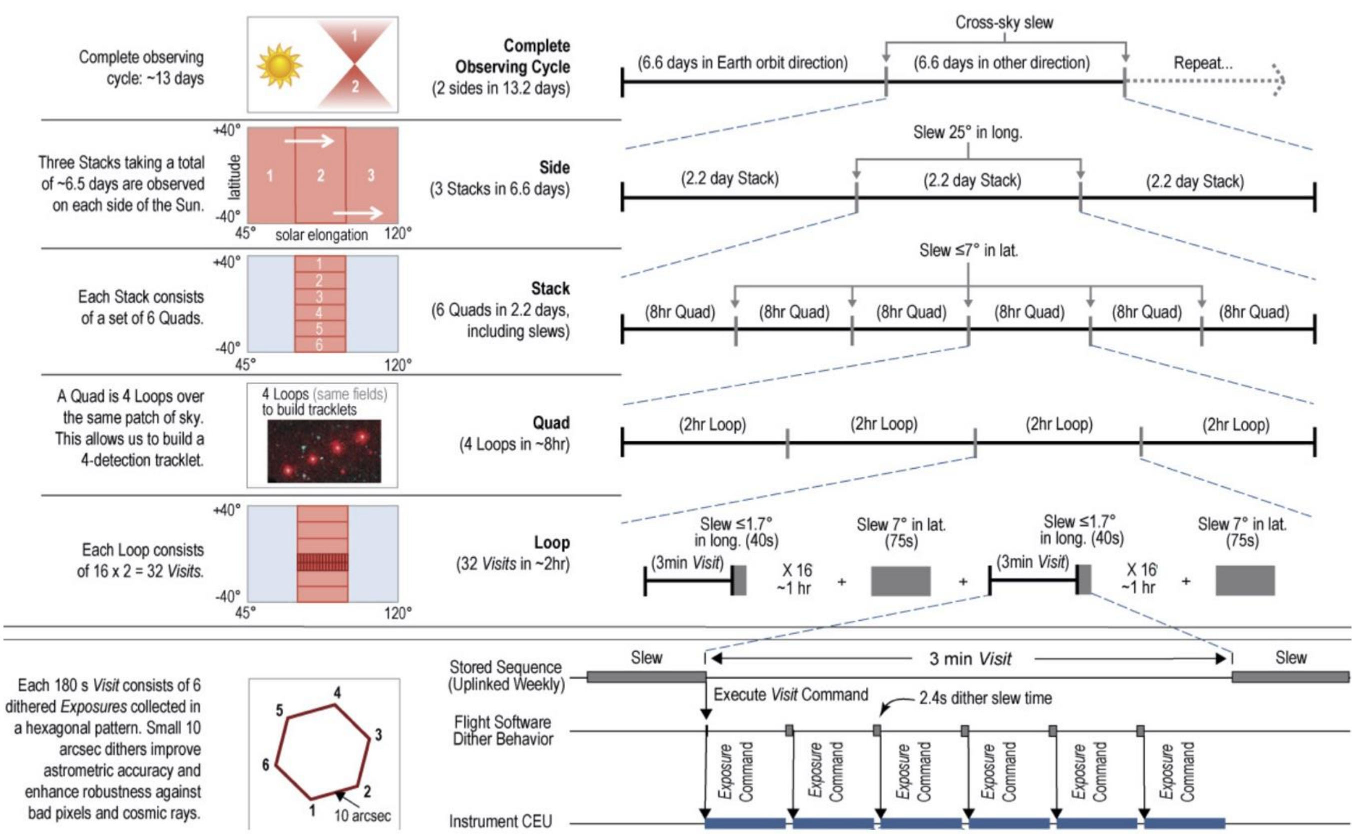

Figure 2: *NEO Surveyor* Survey Pattern

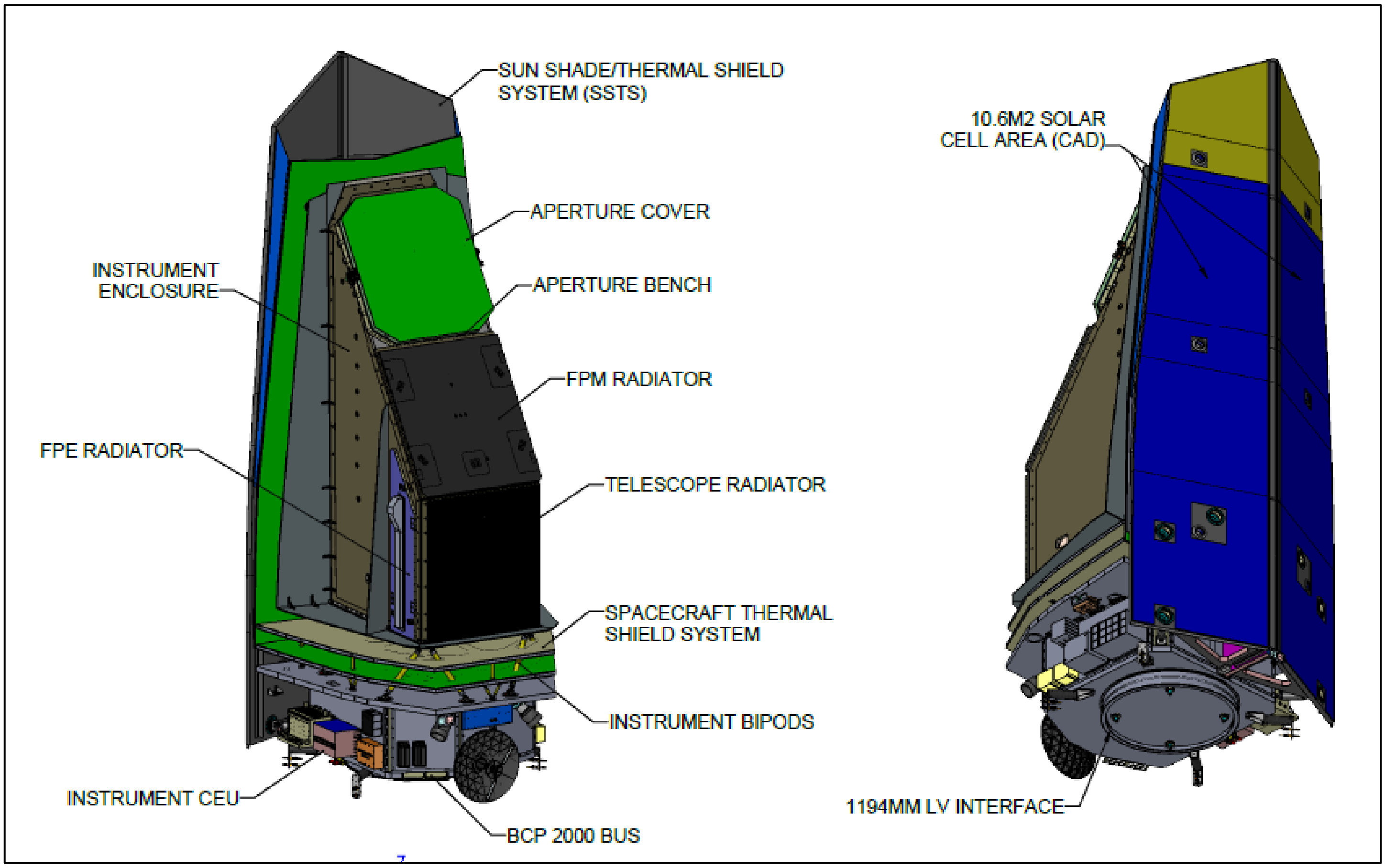

Figure 3: Overview of *NEO Surveyor* observatory.

the sky, this entire process is repeated on the other side of the Sun.

Once per day, the spacecraft points its body-fixed high-gain antenna toward Earth for K-band science downlinks, permitting rapid dissemination of asteroid tracklets to the science community. These 120-min K-band downlink passes are flexible and can occur between any two Visits, allowing the DSN flexibility in scheduling contacts. Real-time commanding and the uplink of pre-planned sequences are performed using S-band. To enable position determination for detected objects, ±15 km 3-sigma reconstructed Observatory position knowledge is required. This is achieved with the planned tracking schedule, which includes five 1-hr tracking passes to ensure geographic diversity to reconstruct the Observatory north-south position: two tracks in the northern hemisphere, two tracks in the southern hemisphere, and one unrestricted pass. Although there is a position knowledge requirement during the survey phase, the *NEO Surveyor* mission design is largely insensitive to the details of orbit design and maintenance. The driving constraints for station-keeping maneuver designs are outer bounds on the orbit size derived from stray light avoidance.

5. Spacecraft Description

Ball Aerospace is providing a Ball Configurable Platform, (BCP) spacecraft for the *NEO Surveyor* observatory (Figure 3). The BCP spacecraft is a proven host for observatory payloads (e.g., *Kepler*, *Wide-Field Infrared Survey Explorer (WISE)/NEOWISE*). The *NEO Surveyor* spacecraft is a fully redundant system which provides the support functions needed by the science instrument during flight. The spacecraft provides a platform stable to 0.5 arcseconds over 30 seconds and supports a communication system with a downlink capability to the Deep Space Network (DSN) of 150 Mbps at K-band. Instrument and spacecraft are thermally isolated by thermal shields and low thermal conductivity structural supports. Three radiators cool the instrument: Telescope, Focal Plane Module (FPM), Focal Plane Electronics (FPE).

Attitude Determination and Control System (ADCS)

The ADCS provides knowledge of the spacecraft orientation by use of sensors. Sensors include Coarse Sun Sensors (CSS), Star Trackers (ST), and a Scalable Space Inertial Reference Unit (SSIRU). The ADCS provides attitude control via a series of torque actuators. These actuators include the Reaction Wheel Assemblies (RWA) and Reaction Control System (RCS) thrusters within the Propulsion system. The ADCS system ensures that the instrument is shielded from the heat of the sun, behind the Sunshade / Solar Thermal Shield (SSTS), at all times.

The ADCS provides the Observatory the ability to meet the mission's stringent pointing accuracy requirements: 250 arcsec. per axis at the start of a Visit, and 2 arcsec., relative to the initial Visit pointing, for each subsequent Exposure within the Visit.

In order to allow the survey to be conducted efficiently, the spacecraft has challenging agility requirements. The 10-as slews between Exposures in a Visit must be accomplished within 2.4s, and the slews between fields within a quad must be accomplished within 40s.

Command and Data Handling (C&DH)

The C&DH system provides the capability to collect, and act upon, telemetry from all the spacecraft systems. The C&DH also ingests ground commands transferred from the telecommunications system. Those commands are processed and routed to the various subsystems for execution. Finally, the C&DH system hosts and runs the BCP spacecraft computer and Flight Software (FSW).

Fault Protection (FP)

The C&DH also includes a Survival Mode Configuration Assembly (SMCA), a fault handling safe hold processor that can take control of the Observatory in reacting to faults, implement redundancy swapping and other responses. This is part of a layered Fault Protection (FP) architecture that also includes hardware-based protections (such as current-limiting switches), as well as a system of highly-configurable, software-based fault monitors and responses.

Electrical Power Distribution System (EPDS)

EPDS handles all the power management functions for the spacecraft. It uses a fixed panel solar array to generate electrical power which is routed to a power distribution system. The power is directed, by means of distribution switches, to the various spacecraft subsystems and instrument on the observatory. Included in the EPDS system is a Lithium-Ion Battery used for power storage. This battery enables the observatory to be powered during launch and to execute rapid acquisition activities, as well as providing a safety net should the electrical loads temporarily out-strip the power provided by the solar array.

Mechanical and Structures (MECH)

The primary spacecraft bus structure supports all the loads which must be transferred from components to the Launch Vehicle (LV) during ascent. The *NEO Surveyor* structure consists of the spacecraft body: an enclosure at the base of the Observatory, housing the spacecraft HW components, and the Sunshade/Solar Thermal Shield (SSTS) assembly, extending up the +Y side of the Observatory.

The enclosure contains the propellant tank, the reaction wheels, and other electronic components. Most of the spacecraft HW components are mounted on the outer walls of the enclosure, allowing their dissipated heat to be radiated into space.

The structural design of the spacecraft meets the primary requirement of supporting all of the HW in the system through the vibrations and shocks of the launch phase, and also the driving need to ensure that the instrument is protected from direct and diffracted sunlight at all times. It also provides the stability necessary to point the telescope as required.

The top of the enclosure, called the spacecraft Top Deck, supports the instrument on kinematic bipod mounts between the spacecraft and the instrument to allow for stable pointing of the cryogenic instrument during survey operations. Additionally, this bipod system serves as a thermal insulator between the warm spacecraft and the cold instrument. Similar insulating strut systems support the Sunshade/Solar Thermal Shield (SSTS) and the Spacecraft Thermal Shields between the instrument and the spacecraft.

Propulsion (PROP)

Propulsion contains all the plumbing, valves, thrusters, tank, fuel, and hardware needed by the spacecraft to perform station keeping or change of plane maneuvers on orbit, as well as the RCS thrusters for momentum management. Working in conjunction with the ADCS, the PROP receives closed loop commands to pulse four Trajectory Correction Maneuvering (TCM) thrusters thereby achieving highly accurate Delta-V burns while avoiding momentum build up due to thrust vector to Center of Gravity (CG) offsets which change due to propellent slosh and consumption.

Telecommunication (COMM)

Telecommunications contains hardware and electronics that provide the capability for uplink/downlink communication with the spacecraft. There are two types of telecom links to the spacecraft (S-band, K-band) allowing *NEO Surveyor* to downlink health, safety, and science data to the ground and allowing the ground to send commands to the spacecraft. The S-band system is used for health and safety telemetry downlink and command uplink. The K-band system provides a high-rate downlink for science data. The S-band system is omni directional, thereby allowing the spacecraft to receive commands at any time and in any orientation. The K-band system utilizes a fixed high gain antenna which the Observatory must point toward the DSN station with high accuracy during science downlink. These science data downlinks are planned to occur once per day.

Thermal System (THERM)

The thermal system maintains all spacecraft components at the correct operating, or survival, temperatures throughout all phases of the mission. The system achieves its mandate through industry standard methods such as cold biasing hardware combined with active heater control. The system includes all thermal blanketing, active heaters, heater control, radiators, thermal shields, and thermal surface finishes.

Sunshade / Solar Thermal Shield (SSTS)

The sunshade provides thermal protection to the payload subsystem from incident solar energy and is a structural element to which the photovoltaic cells and solar thermal shield are attached. The SSTS is precisely integrated once the instrument is installed and cantilevered off the spacecraft structure to complete the *NEO Surveyor* flight system.

6. SPACECRAFT-INSTRUMENT INTERFACES

SSTS and IMLI

The *NEO Surveyor* sunshade, in addition to providing structural mounting for the photovoltaic cells, acts as a shield to intercept direct sun before impinging on the cold instrument. The sunshade is functionally part of the spacecraft. The solar thermal shield is structurally cantilevered off the sunshade, creating a gap. The gap is open ended, and the surfaces forming the gap are specular in the Infrared (IR) wavelength. This allows the warm IR radiation coming off the anti-sun side of the sunshade to largely bounce out, or 'tunnel' to cold space through the open end of the gap. The fraction of heat that is absorbed and conducted from the sunshade to the solar thermal shield is further attenuated before reaching the instrument by using a special type of Multi-Layer Insulation (MLI) called IMLI. IMLI is a patented structure developed by Ball in partnership with a small business through Small Business Innovative Research (SBIR). IMLI uses discrete rigid structures to hold the layers of insulation precisely in place which minimizes conductive shorts and increases insulating efficiency. IMLI can typically achieve the same insulative efficiency with less than half of the layers as traditional cryogenic MLI, which also reduces mass and the conducted heat leak from the sunshade through the struts which support the solar thermal shield. Another advantage of IMLI is the ability to hold its shape in gravity. Typically, a large blanket like this would have significant sagging, shorting and wrinkles in a ground test that would not be flight like. The IMLI will hold its nominal shape during thermal balance testing and therefore will be much closer to the project goal of 'test as you fly'.

The spacecraft thermal shields attenuate the radiated and conducted heat from the warm spacecraft to the cold instrument. This is accomplished by using multiple rigid specular panels to block and shunt IR heat to space as well as stages providing shorting for conducted components such as harness in route from warm to cold regions. Integrated Multi-Layer Insulation (IMLI) is included on the bottom layer to further improve the radiation isolation. A series of low thermally conductive struts mechanically support the spacecraft shield while providing good thermal isolation and a tractable integration scheme.

7. INSTRUMENT DESCRIPTION

Instrument Overview:

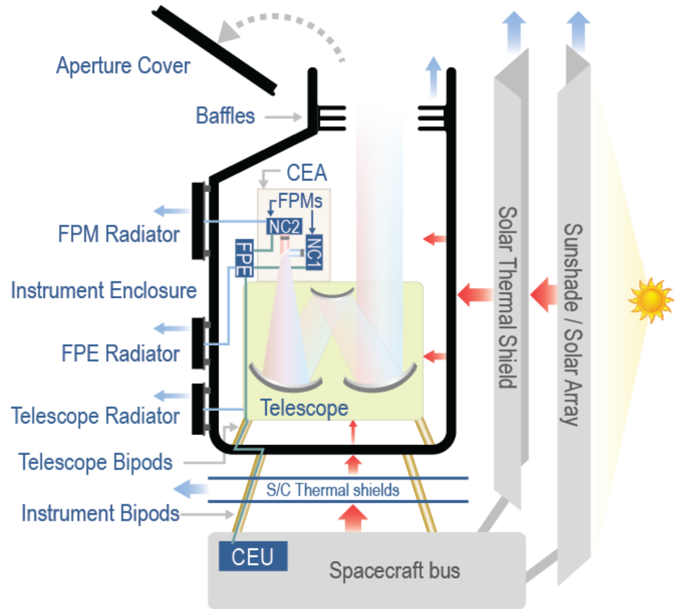

Figure 4: Instrument Architecture

The *NEO Surveyor* spacecraft hosts a single instrument to achieve the required science. The instrument is being developed by several partners (JPL, UA, SDL and Ball). This instrument is a passively cooled (@ 40 K) system with a 50 cm unobscured aperture, wide FOV telescope. Using IR wavelengths, the instrument is optimized to detect NEOs at wavelengths where they are bright, but background stars and galaxies are dim. This is a simple and robust design with no expendables and no moving parts save for a one-time ejectable aperture coverThe *NEO Surveyor* instrument will map the NEOs using Two 16-megapixel HgCdTe detector mosaics, Mid-wave: 57 K for NC1 (4.0-5.2 µm); Long-wave: 40 K for NC2 (6.0-10.0 µm)

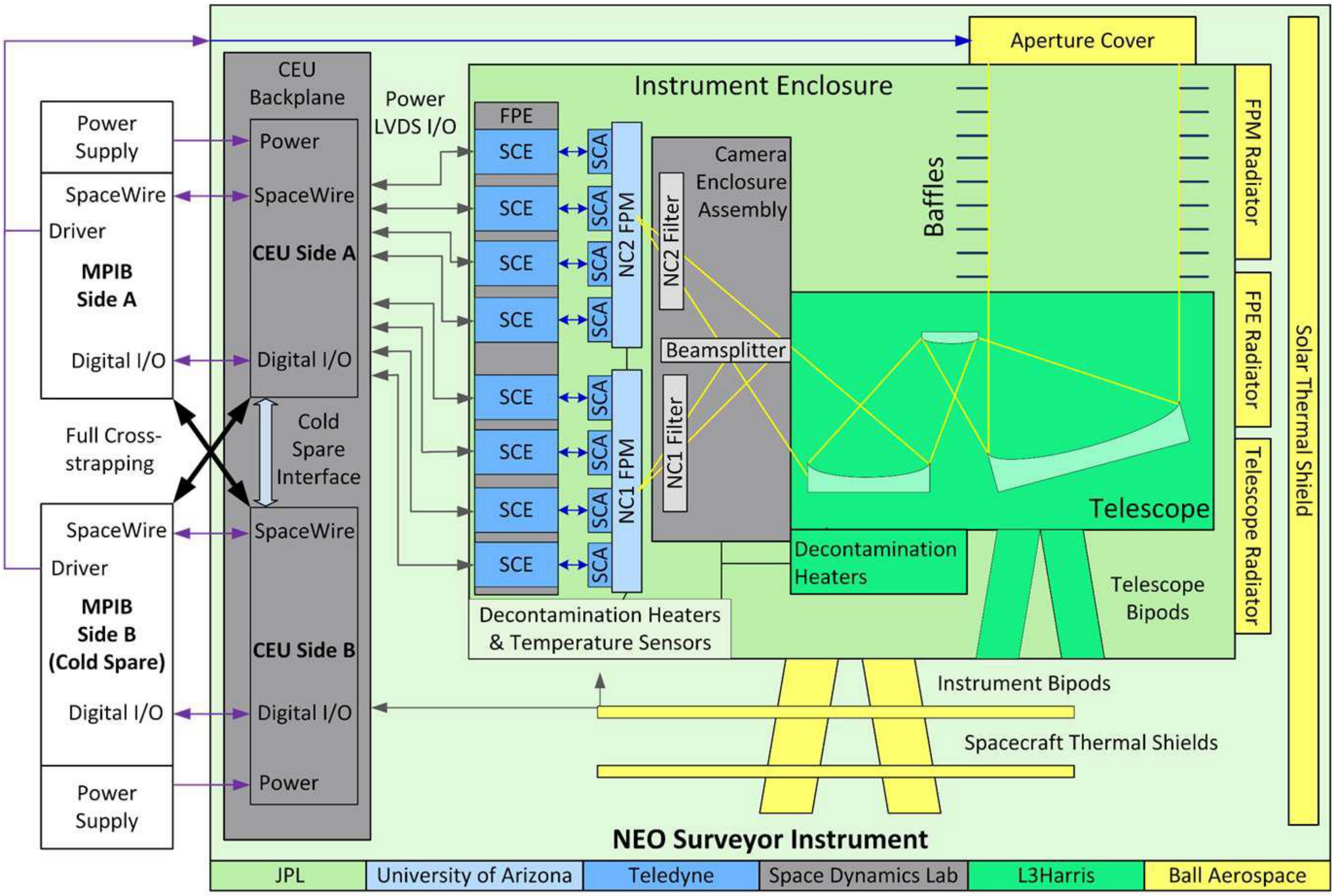

Figure 5: Instrument Block Diagram

The instrument (Figure 4, 5) is a wide FOV telescope with an unobscured 50-cm aperture. The telescope is an all-aluminum off-axis three-mirror anastigmat. The telescope focuses the scene through the camera enclosure assembly (CEA). Baffles provide stray light rejection from the Earth and Moon. The CEA houses a dichroic beamsplitter, and two filters to split the IR light into two channels, NC1 and NC2. The focal plane modules (FPMs) for each channel are housed in the CEA.

To meet the required FOV, each FPM consists of a 1×4 mosaic of sensor chip assemblies (SCAs) provided by Teledyne Imaging Sensors (TIS). TIS's System for Image Digitization, Enhancement, Control, and Retrieval (SIDECAR) controls each SCA. SIDECARs are grouped into the Focal Plane Electronics (FPE) subsystem.

The Central Electronics Unit (CEU), which provides instrument command and control controls the FPE. The CEU performs data acquisition, data processing algorithms, and interfaces the instrument to the S/C. The CEU is mounted in the S/C and controls the instrument heaters and temperature sensors; it draws heritage from the WISE instrument electronics.

The *NEO Surveyor* thermal design uses the 2.7 K ambient environment at the L1 orbit, standard approaches of isolation from heat sources, and cooling via radiators to provide stable instrument operating temperatures. Ball Aerospace lends significant expertise and heritage to the cryogenic architecture of the *NEO Surveyor* instrument. Sunlight is blocked by the solar array mounted to the thermal shield. The solar thermal shield blocks heat transfer from the solar array to the instrument enclosure (IE), which contains and supports the instrument subsystems. The instrument enclosure is coated with Ball Infrared Black (BIRB) to maximize cooling of the instrument structure to space. The aluminum honeycomb IE is mounted to the S/C by S-glass/epoxy instrument bipods. , The bipods are low thermal conductance, high strength, bonded composite tubes with metal end fittings. The bipods are arranged to provide the instrument with a structurally determinate and stable mounting over wide temperature variations. Strength, integrability, and adjustment are all designed into the mechanical features. The bipods will have MLI socks as well as features to minimize the radiative heat transfer within the tube.

The telescope radiator cools the telescope, CEA, and NC1 FPM to <57 K. The NC2 FPM is attached to the CEA on non-conductive mounts and is further cooled by the NC2 FPM radiator to <40 K. The FPE radiator maintains the SIDECARs at <150 K.

Key Elements of the NEO Surveyor Instrument: Telescope:

The off-axis all-aluminum three-mirror anastigmat (TMA) telescope (Figure 7) meets the 50-cm aperture and 1,238-mm focal length requirements. The TMA utilizes free-form surfaces to provide reduced design residual wavefront error and distortion over a flat focal plane. The lack of a central obscuration improves throughput and eliminates diffraction spikes, reducing the rate of false detections.

The light-weighted all- aluminum mirror, bench, and camera enclosure assembly minimizes complexity and costs. Aluminum blanks for the mirrors and structure are prepared using a proven process to obtain temporally and thermally stable Aluminum . The primary and tertiary mirrors are light weighted. Standard computer-generated hologram tests are used for the primary and tertiary mirrors.

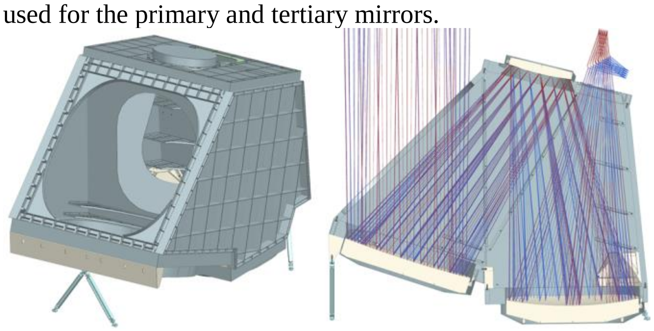

Figure 7: Opto-mechanical configuration of the NEO Surveyor Optical Telescope Assembly

The optical system (telescope and CEA) meets the transmission requirement with margin. The mirrors are used with their native oxide; lack of an overcoat minimizes risks from the coating process. Environmentally induced deformations caused by mount deformations, g-release, and vibration form the largest contributions to the error budget. Secondary effects to the error budget are due to dynamic environmental errors (i.e., thermal), design residual, and alignment errors. The instrument team ruinously tracks these errors to manage margin.

Cryogenic interferometric tests of the telescope will be performed prior to delivery to instrument integration. The individual telescope mirrors and the integrated telescope assembly are tested in two different orientations to account for gravity-induced deformations. The telescope is fabricated from a well-established process that produces temporally and thermally stable low-scatter optics with ~98% reflectivity.

Focal Plane Module (FPM) Architecture:

The FPM (Figure 6) is designed and developed by the University of Arizona, Lunar and Planetary Laboratory. The *NEO Surveyor* instrument contains two FPMs, corresponding with the NC1 and NC2 bandpasses. Each FPM consists four 2K x 2K H2RG SCAs from Teledyne Imaging Sensors in a 4x1 mosaic configuration, with a Midwave Infrared (MWIR) HgCdTe and Longwave Infrared (LWIR) HgCdTe detector corresponding to NC1 and NC2, respectively (Figure 8). The SCAs are operated by Sensor Chip Electronics designed around the TIS SIDECAR electronics implemented in the new NHFPE package designed to meet *NEO Surveyor* environments. The design of the FPM and cables is tightly integrated into the design of the CEA by SDL to ensure

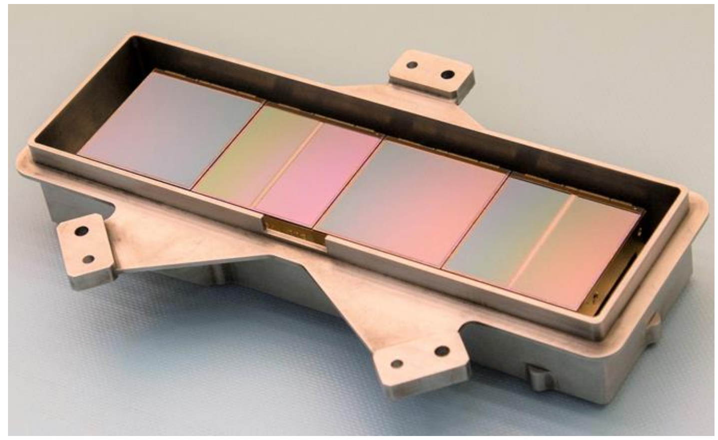

Figure 6: FPM mosaic

maximum performance of the *NEO Surveyor* instrument.

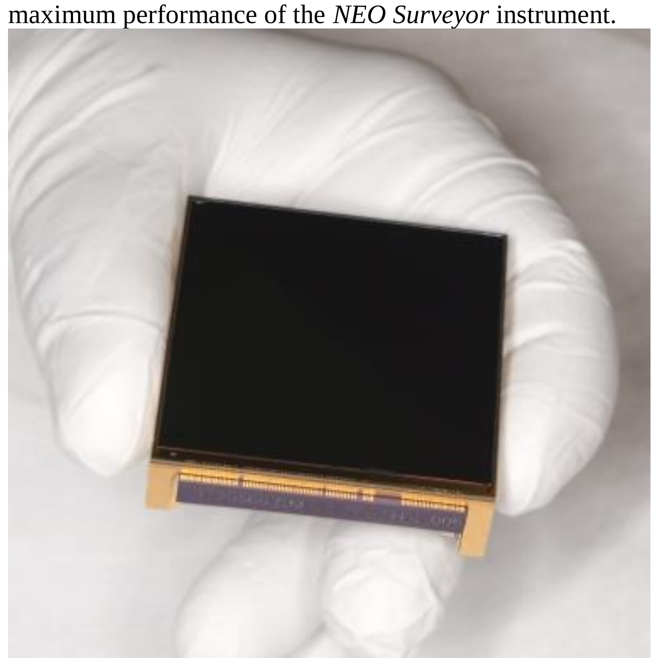

Figure 8: H2RG SCA

The FPE consists of eight (one per SCA) System for Image Digitization, Enhancement, Control and Retrieval (SIDECAR) application specific circuits (ASICs) in a SIDECAR Module (SMd) configuration.

TIS produces a high-performance off-the-shelf MWIR HgCdTe detector that comfortably meets *NEO Surveyor* NC1 requirements while operating up to 75K. TIS has produced 31 MWIR SCAs over the past 5 years meeting the L3 requirements and with the required sensitivity in the 4–5.2

µm NC1 channel, including one on the Four Side Buttable Edge Package (FRSBE) package.

The other detectors in the instrument, the LWIR MCT detectors, are needed to meet *NEO Surveyor*'s science objectives. NC2 SCAs have been fabricated meeting all *NEO Surveyor* requirements. During Phase A, *NEO Surveyor* produced and tested seven NC2 SCAs, with three packaged on the FRSBE package. Radiation testing was performed on the LWIR detectors; no significant degradations from either total lifetime dose or individual particle hits were observed. During the course of testing, each NC2 was cycled to 4 K at least once. Finite element analysis shows no performance difference for thermal or vibration environments between the NC1 and NC2 arrays on the FRSBE package.

Camera Enclosure Assembly (CEA) (Figure 9):
As light leaves the telescope, it enters the CEA and encounters a Ge beamsplitter with a dichroic coating (Figure 10). The shorter wavelengths are reflected towards the NC1 FPM, and the long wavelengths transmit through the dichroic to the NC2 FPM. The backside of the beamsplitter has a weak wedge and weak free-form cylinder to compensate for the aberration introduced by focusing through the tilted beamsplitter. The large wavelength gap between the two channels permits a simpler dichroic design with fewer layers and less overall thickness. Ge has good transmission from 6 to 10 µm. The beamsplitter is held in a flexure mount to minimize mount induced figure changes and to provide positional stability. An EM unit of the CEA was built and tested in Phase A.

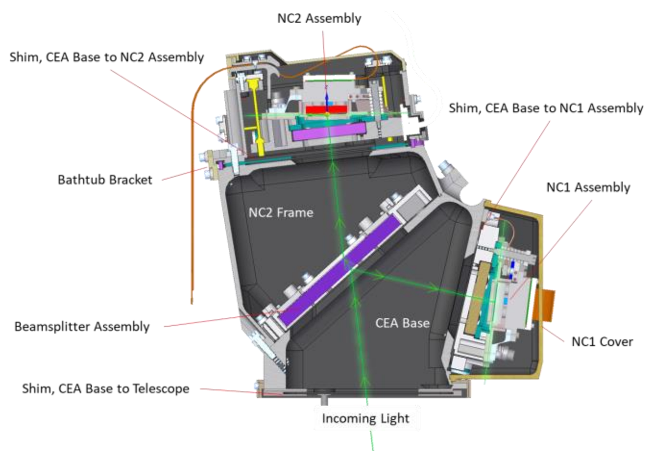

Figure 9: Camera Enclosure Assembly

Immediately before the FPMs are Si (NC1) and Ge (NC2) bandpass filters. Both filter substrates have good transmission in their respective bands and are tough, non-hygroscopic, and readily polished. Coatings are placed on both sides of the beamsplitter and filters to balance stresses at cryogenic temperatures. We have completed preliminary coating designs showing that the spectral bandpass requirements are met and the predicted average transmission of the beamsplitter and filters, including manufacturing tolerances, is ~89% in both channels.

The CEA interfaces to the telescope with a 4-point mount. An aluminum shim and pins are used to precisely position the CEA optics with respect to the telescope optics. The FPMs also interface with the CEA. Prior to focus measurement, athermal shims place each of the focal planes at best focus based on room temperature measurement data for the CEA and telescope. After focus is measured at the maximum and minimum operating temperature, these athermal shims may be modified to place each of the focal planes at best focus.

The optical system (telescope and CEA) exceeds the 70% optical transmission requirement. The band average CBE reflectance and transmission of each optical element includes degradation due to on-orbit contamination losses (2% loss per channel).

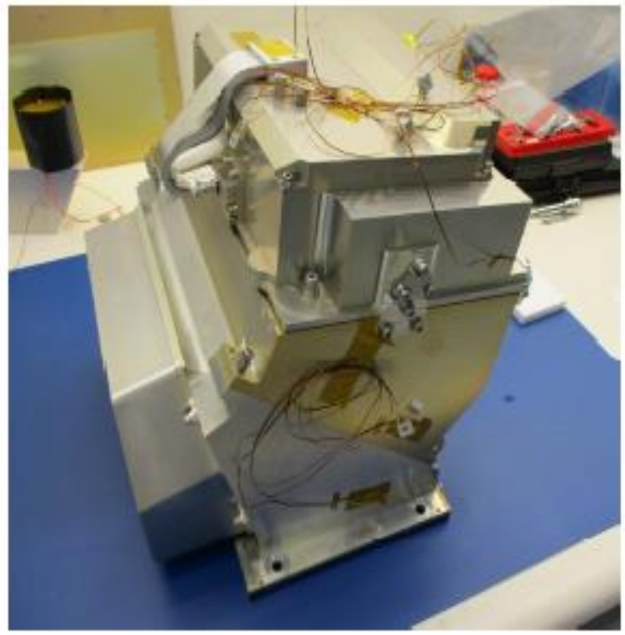

Figure 10: CEA Engineering Development Unit

Thermo-structural analysis of the optical system shows that *NEO Surveyor* does not need a focus mechanism; mechanical shims are utilized. Because the telescope mirrors and structure are all Aluminum, the design is inherently athermal.

Instrument Electronics: Central Electronics Unit (CEU)

The instrument electronics interface the FPEs to the S/C and control the instrument heaters and temperature sensors. The CEU is implemented in a fully redundant configuration: a CEU cold spare is provided to complement the cold spare architecture of the S/C. The S/C to CEU interface provides full cross strapping of control and data buses, which maximizes control flexibility and reliability.

The CEU contains a total of 17 circuit cards. eight circuit cards are used for the primary electronics side (A) and eight circuit cards for the redundant electronics side (B). One backplane card is used to connect cold spare signals between the sides. Each CEU boards is approximately eight inches wide and plugs into the backplane that is common to each side of the CEU.

The CEU provides three basic functions. First, the CEU power supply card filters and converts S/C unregulated voltage to the required voltage levels for the CEU and FPE. Second, the S/C interface card is the master controller for the CEU, which processes S/C commands and collects processed science data from each of the FPE Interface boards. The logic and control of the S/C interface cards is implemented in an FPGA. Temperature monitoring and heater control are also performed on the S/C interface card. Third, each FPE Interface card interfaces to four SIDECARs and provides the bias, control, and data interfaces for each SIDECAR. The complete assembly is housed in a common chassis and mounted in the S/C.

There are two primary electrical interfaces, CEU-FPE and S/C- CEU. The CEU-FPE interface is implemented through the CEU via an LVDS interface for all clock and data lines. All FPE signals are routed to the CEU via 8 separate harnesses, where they connect to LVDS drivers and receivers. CEU Cold sparing enables a redundant LVDS device to be tied to the data bus with its power supply at 0 V without affecting the bus signals or injecting current from the I/Os to the power supplies. Cold sparing also enables the redundant boards to be powered off and switched on only when required.

The S/C to CEU interface is implemented using a 40 MHz SpaceWire link for both command and data. The logic and transport layer uses a simple command and response protocol. The S/C to CEU interface is fully cross strapped such that S/C side A and side B can communicate with either CEU side A or CEU side B.

Instrument Enclosure:

The instrument enclosure (IE) and supports are the primary structure for the instrument. Together these structurally integrate the S/C bus, telescope, aperture cover, and all radiators into the observatory (Figure 11).

Importantly, the IE provides thermal isolation necessary for a passively cooled observatory, along with stray light mitigation. The enclosure is built from aluminum honeycomb panels bolted and pinned together. This provides a low-cost, low-mass, high-stiffness solution to this important piece of structure. Aluminum honeycomb is ideal from a thermal standpoint: high in-plane thermal conductance minimizes gradients and efficiently transports heat to where it is to be radiated away.

The interior surfaces are of necessity optically black for stray light mitigation, and hence are also high emissivity for additional passive cooling. An array of baffles on the interior surfaces prevents any direct enclosure sidewall view to the tertiary mirror, eliminating the primary source of stray light.

The instrument bipods are fabricated from S-glass epoxy tubes. S-glass has minimum thermal conductivity for the required loading compared to other composites. End fittings of titanium complete the structural picture, giving the bipods robust margins, since they dominate instrument strength (for G loads) and stiffness (for high modal frequencies). This architecture also has extremely low thermal conductance, and, in concert with the S/C thermal shields, prevents heat from the S/C bus from reaching the IE.

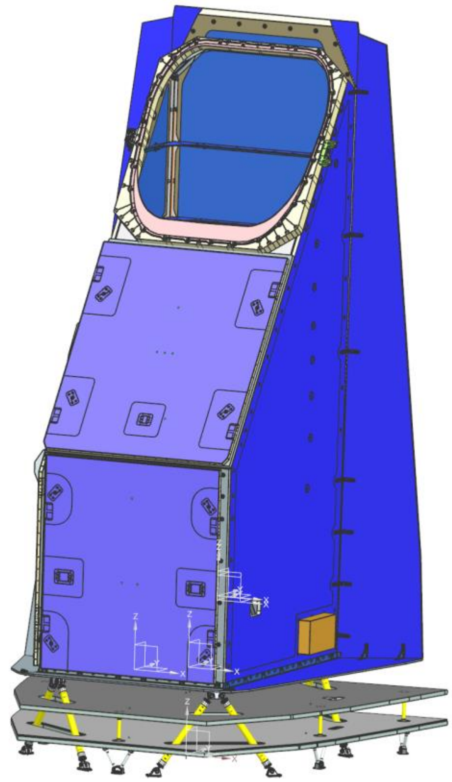

Figure 11: Instrument Enclosure

The S/C thermal shields prevent a radiative view from the S/C bus to the instrument. Aluminum honeycomb construction is used to optimize heat transport.

The S/C thermal shields are supported from the S/C bus using W-trusses of S-glass epoxy tubes for high stiffness, low thermal conductance, and compliance to temperature differences between the shields and bus.

Deployable Aperture Cover

The only release mechanism on the *NEO Surveyor* instrument is for ejection of an aperture cover that shields the telescope from light and dust contamination during ground handling and launch operations. The aperture cover is attached to the main enclosure of the instrument during Assembly, Integration and Test (AI&T) storage and launch. Once the observatory in in a safe state, a latch is released that allows the aperture to open along a spring-loaded hinge (Figure 12). After fully opening, the hinge ejects the door permanently. This design leverages heritage from the successful *Kepler* mission and *Spitzer* space telescope observatory. Only minor engineering modifications are made to the previous design to accommodate variation in size and geometry of the *NEO Surveyor* telescope structure.

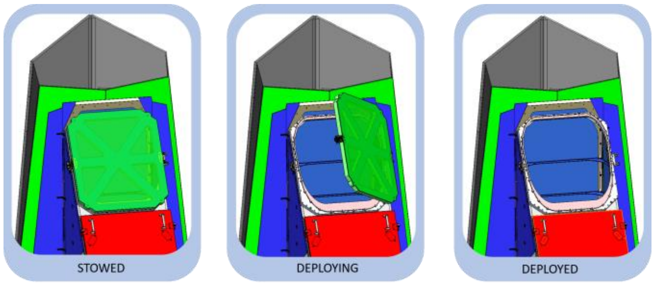

Figure 12: The aperture cover deploys using a latch and hinge, dual-point mechanism in order to safely eject away from the observatory

Thermal Subsystem:

Elements of the *NEO Surveyor* instrument system must operate at cryogenic temperatures to attain the performance required to meet the Science Objectives: the telescope must operate at ≤57 K for natural background-limited performance, and the NC2 FPMs must operate at ≤40 K to minimize detector dark current. The FPMs and the FPE must be stable to within ±0.05 K over 24 hours and ±1 K over five hours, respectively.

The *NEO Surveyor* passively cooled instrument system achieves the required temperatures by taking advantage of the 2.7 K deep space radiative heat sink. This in combination with the application of well-understood principles of reflective shielding, reducing heat dissipation, and use of Multi-Layer Insulation (MLI), low conductivity materials, and high emissivity radiators allows the required temperatures to be achieved. Our passive cooling approach has no moving parts to wear out and no consumables, leading to a simpler system with fewer potential failure modes and therefore increased reliability and mission lifetime over active systems.

Passively cooled cryogenic systems have been demonstrated successfully, and their performance was accurately predicted. *NEO Surveyor* borrows the Spitzer Space Telescope's thermal shield design concept, with additional radiators to cool the FPE, telescope, and NC2 FPM.

The NEO Surveyor instrument uses these proven processes, procedures, and analyses to design a passively cooled thermal system that meets the functional requirements. Numerical models built in Thermal Desktop® show robust margins for the key and driving parameters, in particular the heat load margin (or cryo margin), which will be tracked to ensure required cryo margin levels are met throughout the entire project life cycles. The required temperature stability of FPMs and FPE is ensured by feedback-controlled heaters powered by the CEU. The thermal subsystem also ensures successful decontamination of the optics during transient cooldown phase, the safety of the instrument components in the event of anomalous short-duration sun exposure, and limits thermal distortion to achieve the required pointing accuracy and stability.

Reflective shields and MLI isolate the IE from the hot S/C bus and sunshade. A Ball IMLI blanket on the solar thermal shield insulates the IE from the hot sunshade, while an IMLI blanket on the S/C thermal shield insulates it from the hot S/C Bus. Another blanket on the S/C top deck reduces heat flow to the S/C thermal shields. Low emissivity thermal shields reflect incident heat to space. The IE is supported off of the S/C top deck by four low thermal conductivity S-glass bipods. The S/C thermal shields are supported by a separate thermally-isolating support system.

Heat that reaches the IE is radiated to space by large areas of high-emissivity Ball IR Black (BIRB) paint. BIRB Coating has heritage to the *Spitzer* mission and further developed on *JWST*, which is currently in preparation for launch in late 2021. BIRB provides excellent cryogenic emissivity performance for large surface areas. BIRB measured performance (Figure 13). BIRB is used on both the instrument enclosure and the three dedicated radiators. The instrument enclosure acts as its own radiator and benefits from an unobstructed view to space. Applying BIRB to various portions of the enclosure reduces the temperature of the cryogenic components.

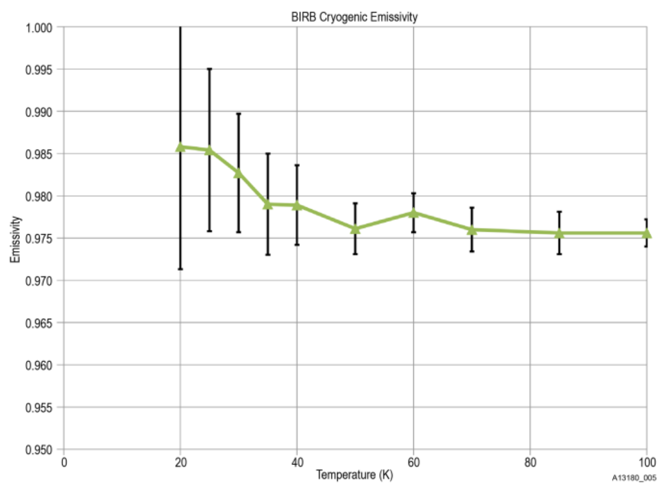

Figure 13: Measured Performance of BIRB shows high emissivity at cold temperatures

In order to achieve adequate sensor performance, *NEO Surveyor* employs three radiators (Figure 14). Thermal shields and black IE sides act as the first cooling stage. The telescope radiator (second stage) cools the telescope, CEA housing, and NC1 detectors to ≤57 K. The NC2 FPM radiator (third stage) cools the NC2 detector to ≤40 K. The FPE radiator is mounted to the side of the telescope structure. The modeled operating temperature of the FPE radiator is ~94 K. All three radiators are mounted to the instrument enclosure using heritage, high thermal impedance flexures and posts.

Mechanically compliant, high thermal conductance straps couple the radiators to the hardware.

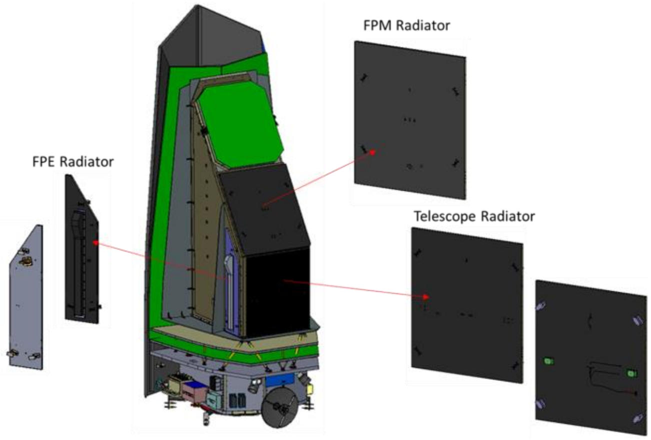

Figure 14: Three radiators are specifically designed to independently regulate waste heat from the FPE, FPM, and telescope using high emissivity BIRB

Thermal Test Program:

The thermal test program retires risk during the development and verifies the entire thermal system. The flight system is designed to have three separately testable zones allowing for high confidence verification of thermal performance during difference project phases.

The earliest test is the External thermal balance (ETB) test at Ball, which uses the flight IE, radiators, and thermal shields to verify passive cooling performance in the 40-200 K external zone. This zone includes radiators and shields between the instrument enclosure (IE) and S/C (Bus and Sunshade).

The second test is the Internal Thermal Balance (IBT) test during instrument integration at SDL, which verifies milliwatt level heat flows in the 40-57 K internal zone, as well as temperature control and temperature stability for various components. This zone includes the telescope, CEA, FPMs, and FPE, with the goal of limiting heat to the NC2 FPM for it to operate below 40 K.

Finally, the Observatory-level Thermal Balance test measures the sunshade and S/C temperatures in the 286-368K S/C zone. This zone includes the S/C and solar panels, and is driven by the electronics temperatures and solar flux absorption.

All three tests combined provide a complete thermal verification of the passive cooling system with only minimal corrections to compensate for test conditions.

Final Instrument I&T Program:

NEO Surveyor Instrument Integration has some key challenges to work thru across multiple partners and locations (JPL/UA/Ball/SDL). The primary instrument Integration is slated to happen at Space Dynamics Laboratory (SDL) in the Thermal Optical Research (THOR) Chamber (Figure 15). The Instrument Enclosure & Telescope will go through independent subsystem I&Ts prior to delivery to SDL for final Instrument Integration. The challenges lie in sequencing the integration flow and the final test and calibration campaign of the entire instrument and ensuring safety of the hardware and maintaining the delivery schedule.

The instrument integration begins at SDL with integration of the flight telescope, CEA, and IE. The telescope, CEA, and IE are assembled and aligned to prepare for stray light testing.

Figure 15: SDL's THOR chamber

SDL's stray light test facility, known as the Black Hole, is specifically designed for testing the off-axis rejection of optical instruments. The facility provides a collimated beam as input to the instrument which is mounted on a rotation stage and is capable of characterizing off-axis rejection down to 9 orders of magnitude. After the test verifies the baffle and stray light designs, the flight FPMs and CEU are integrated and instrument closeout is performed. Functional testing at ambient temperature is performed, and the instrument is prepared for requirements validation in an operational environment.

SDL performs the instrument focus, thermal balance, and calibration using existing GSE uniquely suited to test *NEO Surveyor* across the full FOV at operational temperatures. The instrument and a cryogenic extended source are mounted within the THOR chamber, a cryogenic vacuum chamber that uses 80 K shrouds and helium GM cryocooler circulation systems capable of establishing thermal test boundaries. The THOR chamber is mated to the Multi-function Infrared Calibrator (MIC5). The MIC5 provides cryogenically cooled, low background collimated source configurations including simulation of a point source for focus and point response function (PRF) evaluations. The THOR chamber and MIC5 share a common vacuum eliminating the need for a window.

Gate valves are used to change the MIC5 interface flanges in situ, allowing for full aperture coverage over the *NEO Surveyor* FOV.

The instrument test plan includes two focus verification tests over the full FOV at nominal, warm, and cold predicted on-orbit temperatures before vibration testing. A key requirement during I&T is to focus the instrument for the on-orbit environment. The MIC5 provides a cold background IR point source target to the instrument that is imaged on both the NC1 and NC2 FPMs. Wave Front Error (WFE) performance is measured across the field and through focus; the focus data are combined with as-built optical models to analyze and determine the best-focus position across the field for both channels. The instrument is then returned to ambient conditions where NC1 and NC2 FPMs are independently adjusted along focus and tip/tilt per the as-measured data. This operational TVAC test is then repeated to confirm focus is within specification. This method of focus testing has been successfully used at SDL for focusing multiple IR space telescopes.

Instrument performance is characterized with an engineering calibration prior to vibration and acoustic testing. After vibration and acoustic testing, a thermal balance test of the instrument is performed. The thermal balance test generates expected on-orbit boundary conditions and measures instrument temperatures and gradients for thermal model correlation. Separate thermal zones simulate the hot and cold instrument interface temperatures. After thermal balance, the instrument is ready for calibration.

The calibration of the instrument's image quality, radiometric, goniometric, and spectral performance is performed at nominal, warm, and cold operating temperatures in the THOR chamber. The calibration tests collect the data required to verify the instrument sensitivity and other key instrument performance requirements. Spectral response measurements are made by feeding MIC5 with a beam modulated by a Fourier transform spectrometer.

7. CONCLUSION

The *NEO Surveyor* project, which is currently under development, will offer the first chance to detect and characterize the majority of the potentially hazards asteroids >140m. This mission requires the expertise and contributions from several partners for both the instrument and the spacecraft development. The requirements are met by the spacecraft utilizing a proven capable bus derived from the Ball Aerospace BCP product line. The instrument achieves the requirements using a robust passive thermal design and highly sensitive IR components. The integration and test program has been thought through to ensure that the on-orbit performance will meet the science goals with known margin. Finally the mission design will provide for a simple repeating pattern of observations from the L1 point which will provide data to find PHAs before they find us.

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BIOGRAPHY

Tom Hoffman *is currently the Project Manager of the NEO Surveyor project at Jet Propulsion Laboratory, California Institute of Technology. Until recently he was the Project Manager of the InSight project. InSight is the most recent US Mars lander. Has worked on several successful JPL flight and technology programs including Voyager, Cassini, STARDUST, Mars Exploration Rovers, and the GRAIL lunar mission.*

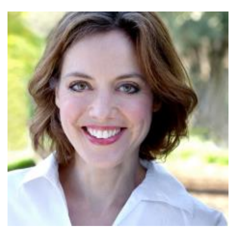
Mark Rokey *serves as the Mission System Manager for NEO Surveyor, overseeing development of the mission operations and ground data systems. Prior to this, he served as Mission System Manger for both the SunRISE and CloudSat missions, and was the Flight Director for CloudSat during its prime mission. He has also held flight positions on Shuttle Radar Topography Mission (SRTM), the Spaceborne Imaging Radar (SIR-C) Mission, the Venus Magellan Mission, and was lead for Ground Systems on JPL's Advanced Projects Design Team.*

Mar Vaquero *is the Mission Design and Navigation Team Lead for the NEO Surveyor mission. At JPL, her work is focused on finding ways for spacecraft to fly accurately and safely around the solar system using little to no fuel. Mar has worked on multiple projects, ranging from developing early mission concepts to navigating the Cassini spacecraft through its Grand Finale.*

TJ Sayer *is the Chief Engineer for the Ball Aerospace portion of the NEO Surveyor program (Spacecraft, Instrument Components, Observatory I&T). During 20 years of Spacecraft development, he has worked on many missions including: ORBCOMM Generation 2 constellation replenishment, TacSat-2, and DSX.*

Dr. Michael Veto *is currently an Advanced Systems Manager for Civil Space New Business at Ball Aerospace. Dr. Veto is the PI on the Reduced Envelope Multispectral Infrared Radiometer (REMIR) for the Sustained Land Imaging Technology research and development program and leads instrument systems engineering and business development to support NASA Announcement of Opportunities. He is payload downlink lead for CIRiS, a NASA InVEST currently in LEO. For his PhD thesis with Prof. Phil Christensen, he was PI for the Thermal-camera for Exploration, Science, and Imaging Spacecraft (THESIS) for Georgia Tech's Prox-1 microsat mission; prototyped infrared focal planes for TRL maturation in preparation for E-THEMIS on NASA's Europa Clipper; supported TVAC on OSIRIS-REx—OTES; and studied explosive volcanism and impact cratering on the surface of Mars with 2001 Mars Odyssey—THEMIS*

Pavani Peddada *is currently the Instrument System Manager on NEO Surveyor at Jet Propulsion Laboratory, California Institute of Technology. Until recently she was the Deputy Payload Manager on EUROPA Clipper and before that the Payload Manager for SENTINEL-6A (US Payload). She has worked on several successful JPL flight and technology programs including MSL Chemin Instrument, WFIRST Coronagraph, FOUO & Classified Instrument Development, and Advanced Mirror Testbed.*



Dr. Amy Mainzer *is the Survey Director for the NEO Surveyor, as well as the Principal Investigator for the NEOWISE mission. She is a Professor in the Department of Planetary Sciences at the University of Arizona and is an expert in asteroid and comet detection and characterization. Prior to that, she was a Senior Research Scientist at the Jet Propulsion Laboratory and served as the Deputy Project Scientist for the WISE mission. She was responsible for the fine guidance sensor on board the Spitzer Space Telescope*

Dr. Mark Lysek *is the NEOCam Instrument System Engineer. His areas of expertise include cryogenic design, analysis, test, and systems engineering of optical, planetary and fundamental physics instruments. Until recently he was the Technical Group Supervisor of the Applied Low Temperature Physics Group, he supported engineers on projects including the JWST/MIRI cryocooler, Planck Cryocooler, and the Low Temperature Microgravity Physics Facility. He was the step 1 instrument manager for the NEOCam Discovery proposal and thermal System Engineer for the MSL CheMin Instrument. As the Cryogenic System Engineer for Spitzer project during phase A, he developed the cryo/thermal architecture and built detailed thermal models of candidate designs.*

Alex Murray *is a senior systems engineer in the Fault Protection and Autonomy Group at JPL. Currently lead flight system systems engineer for the NEO Surveyor mission, he has previously done flight systems engineering on several JPL missions, including Psyche, Sentinel-6, Europa Clipper and InSight as well as systems engineering on Earth-orbiting science missions. Also did and led software development for flight, ground, and simulation software for missions and for technology development projects at JPL. Former systems engineer for the European weather satellite agency, EUMETSAT, and software engineer for the Dresdner Bank, Frankfurt. BS and MS, Mathematics, Ohio State University.*

Erik Nilsen *is the Deputy Project Manager and Flight Systems Manager for NEO Surveyor Project at the Jet Propulsion Laboratory. He was the Proposal Capture Lead for the NEOCam proposal and the Deputy Project Manager for the NEOCam Extended Phase A activities. He has extensive experience in mission formulation, managing multiple proposals for Earth Science, Astrophysics and Planetary missions, and worked most recently as the Advanced Studies Manager for Mars Sample Return. He has a BS and MS in Electrical Engineering and an MBA, with 31 years of experience at JPL.*

Andre Wong *is an engineer for the University of Arizona, Lunar and Planetary Laboratory leading the development, test and delivery of the Focal Plane Modules for the NEO Surveyor project. He has a background in astronomy and has worked previously for the Jet Propulsion Laboratory as an engineer for the Flight Instrument Detectors and Camera Systems Group supporting various programs including Deep Space Optical Communications and ECOSTRESS.*

Yuanming Liu *– Thermal/Cryo Engineer. Y. Liu holds a PhD in Low-temperature condensed-matter experimental Physics from the University of Washington. He has 25 years of JPL working experience with expertise in low-temperature high-resolution instrumentation and precision measurement (Insight Pressure Gauge calibration), cryogenic instrument design and build (LTMPF), thermal fluid flight hardware design, fabrication, and test (MSL, M2020), system-level TVAC and thermal balance test (SIM, AMT, MSL), and thermal analysis with thermal math modeling (MSL mechanisms and NEO Surveyor).*

Paul Snider *received his BS Degree in Mechanical Engineering from the Kansas State University in 1992. He is a Senior Program Manager in the Civil Space Strategic Business Unit, and has 25 years of experience at Ball Aerospace including over 15 years of space hardware integration, test and launch experience with Ball for civilian, commercial and defense customers - including international experiences. His accomplishments include management of several firm-fixed price and cost-reimbursable programs, and capital projects with budgets ranging from under $10 million to over $350 million. His recent flight programs include Deputy Program Manager for the JPSS-1 Satellite, Program Manager for the MethaneSAT Satellite and Program Manager for the NEO Surveyor Spacecraft and Instrument cryogenic hardware. In addition to flight program management, Mr. Snider has also supported numerous proposals as capture manager, proposal manager, program manager and technical manager for Civil Space and National Defense business units.*